

One-dimensional linear array of cylindrical posts for size-based deterministic separation of binary suspensions

Raghavendra Devendra^{a,b} and German Drazer^{a,b}

^a *Department of Chemical and Biomolecular Engineering,
Johns Hopkins University, Baltimore MD 21218 USA. and*

^b *Present Address: Department of Mechanical and Aerospace Engineering,
Rutgers, The State University of New Jersey,
Piscataway NJ 08854 USA. E-mail: german.drazer@rutgers.edu*

Abstract

We investigate the motion of suspended particles past a single line of equally spaced cylindrical posts that is slanted with respect to the driving force. We show that such a one-dimensional array of posts can fractionate particles according to their size, with small particles permeating through the line of posts but larger particles being deflected by the steric barrier created by the posts, even though the gaps between posts are larger than the particles. We perform characterization experiments driving monodisperse suspensions of particles of different size past the line of posts over the entire range of forcing orientations and present both the permeation probability through the individual gaps between the posts as well as the fraction of permeating particles through the one-dimensional array. In both cases, we observe a sharp transition from deflection to permeation mode that is a function of particle size, thus enabling separation. We then drive binary mixtures at selected orientations of the line of posts and demonstrate high purity and efficiency of separation.

I. INTRODUCTION

An important unit operation in a variety of lab on a chip systems is the separation of suspended mixtures of species. As a result, a number of microfluidic devices have been created either to miniaturize conventional separation techniques or to implement novel separation strategies. [36, 37, 44, 50] Different aspects of the separation process are emphasized depending on the application, but a common trend is the development of continuous separation processes, which can be readily integrated with downstream operations in a lab on a chip platform.[4, 12, 23, 25, 33, 34, 45, 48, 51? , 52]

Deterministic lateral displacement (DLD) is a particularly promising, two-dimensional continuous separation method to fractionate a mixture of suspended species.[20, 24] In this technique, components of different size migrate in different directions as they are driven through a periodic array of cylindrical posts. DLD has been successfully implemented for the fractionation of diverse samples.[9, 10, 18, 22, 38, 39] In previous work, we investigated the mechanisms leading to separation in DLD and demonstrated an alternative operation mode, in which suspended species are driven through a two-dimensional (2D) array of posts by a constant force, specifically gravity (g-DLD). [2, 6, 12, 15, 21, 30? ?] The motion of suspended particles in DLD shows directional locking, in which the migration angle remains constant and equal to a lattice direction over a finite range of forcing orientations.[15] In particular, for small enough angles between the external force and a line of posts corresponding to a column (or a row) in a square array, the particles move down a lane between two adjacent columns (or rows) without crossing them. Previous experiments also established that, as the forcing angle increases (from zero), there is a critical transition angle, above which the particles are able to move across columns in the array. [12] This critical transition angle depends on particle size, thus allowing for separation. Moreover, the highest resolution of separation in a binary mixture was found to occur near the critical transition angle.[12] These results suggest that a single line or a one-dimensional (1D) array of cylindrical posts in lieu of the entire 2D array, could in principle, be used to fractionate a mixture of particles.

Here, motivated by the results discussed above, we investigate the motion of suspended particles driven past a slanted line of uniformly spaced cylindrical posts by a constant external force. We demonstrate that such a 1D array of posts can, in fact, fractionate a mixture of suspended particles with high purity and efficiency. More specifically, we shall

show that, depending on the angle between the line of posts and the external force, large particles will be deflected sideways whereas small particles will permeate through the 1D array of posts. It is important to note that the gap between the posts is larger than the largest particles used here. On the other hand, the deflection of particles of a given size is only possible when the *projected gap*, that is the gap between posts projected in the direction of the driving force, is smaller than the particles. This introduces a different approach to separation based on a steric barrier (the 1D array of posts) that is different from a traditional membrane or filter.

II. MATERIALS AND METHODS

A. Device fabrication and experimental setup

The devices were fabricated using photolithography in a clean room. A negative photoresist (SU8-3025) was spun coated on top of a standard microscope glass slide, exposed to UV light and developed to obtain a line of cylindrical posts on the glass slide. The thickness of the photoresist and therefore, the height of the resulting posts, was approximately $40\mu\text{m}$. The profile of a fabricated line of posts obtained with a 3D Laser Scanning Microscope VK-X100/X200 (Keyence Corp., Japan) is shown in Figure 1. The measured diameter of the posts is $2R = 19.5\mu\text{m}$ and the centre-to-centre separation is $\ell = 40\mu\text{m}$. Several of these lines of posts were fabricated on a single glass slide. Individual lines of posts were separated by $1000\mu\text{m}$ from each other to avoid any effect on the particles moving past a given line from a neighbouring line. The lines were used singularly in independent experiments. The diameter of the posts and the spacing between them were designed to be comparable to the diameter of the largest particles used in the experiments.

The lines of cylindrical posts were surrounded by double sided adhesive tape (Grace Bio-Labs, Inc., OR) to create a containing well on the glass slide. We performed experiments using silica particles with a density of 2 g/cm^3 and average diameter of $4.32\mu\text{m}$ (Bangs Laboratories, Inc., CA), $10\mu\text{m}$, $15\mu\text{m}$ and $20\mu\text{m}$ (Corpuscular Inc., NY). The particles were suspended in 0.1 mM aqueous KOH solution (to prevent sticking). They were then introduced into the well and allowed to settle down at the bottom of the device. Without trapping any air inside, the well was sealed using a glass cover-slip (and double sided adhesive tape) to

eliminate the possibility of convective effects. The device containing the suspended particles was then mounted on a microscope and the microscope was tilted at an angle, $\phi = 16^\circ$, thus exploiting gravity to drive the particles down the slide and past the line of cylindrical posts. More details on the experimental procedure can be found in reference 12.

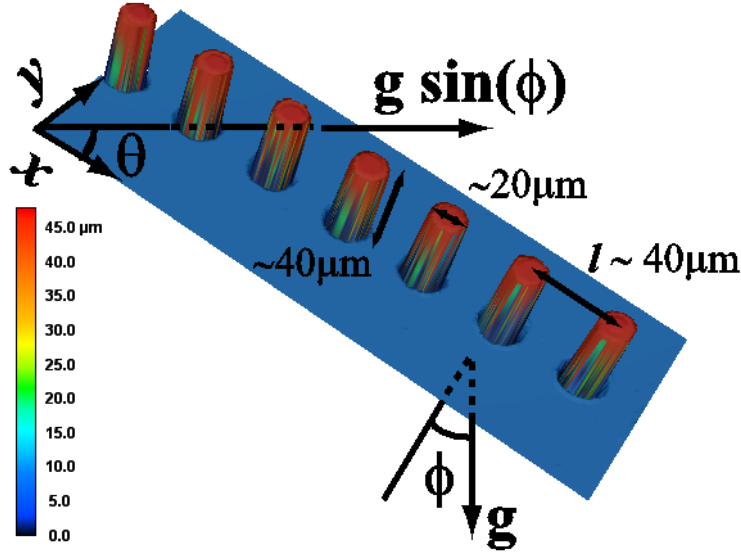


FIG. 1. Three-dimensional image of the device indicating the microscope tilt angle ϕ , the forcing angle θ , diameter of the posts $2R \approx 20\mu\text{m}$, the spacing between the posts $\ell = 40\mu\text{m}$ and the height of the posts $\approx 40\mu\text{m}$.

B. Image acquisition and data analysis

Images were captured at a frame interval of 2s in bright field, using a Rolera Mgi+ EMCCD camera (Q-imaging, BC) and IP lab software (Biovision Tech, PA). We used manual tracking plugin (by Fabrice Cordelieres) in ImageJ (NIH, MD) to track the particles. The field of view consisted of 21 posts. The stream of particles was not focussed from a single starting point and as a result, the first interacting post for a given particle could be any one of the posts in the field of view. The forcing angle, θ , is defined as the angle between the direction of the driving force (gravity projected onto the plane of the device i.e. xy -plane in Figure 1) and the line of posts (x -axis in Figure 1) and was measured by tracking particles in an (open) area free of posts. Experiments were performed independently at

forcing angles with no particular increasing or decreasing order to avoid any cumulative error or correlation between the experiments. We only considered particles that travelled at least $100\mu\text{m}$ in the driving direction to reduce any fluctuations in the value of the measured forcing angle. The particles moving in the open area and those interacting with the posts were tracked separately. Approximately, 20 particles were tracked in each experiment for a given forcing angle and a given particle size. In order to minimize the effect of polydispersity in the supplied particles, especially $10\mu\text{m}$, $15\mu\text{m}$ and $20\mu\text{m}$ particles, we used calibration scales during tracking and considered only those particles within 10% of the specified size. In order to capture the behaviour in the dilute limit, the trajectories of particles that interact with another particle were discarded. On occasions, where a large particle blocked a spacing between the posts, the trajectories that interacted with such stuck particles were split into separate trajectories by cropping out the periods during which the interactions with the stuck particles took place. In rare instances, if a post was significantly different in size and shape from the design, the particles that interacted with that specific post were eliminated from the analysis.

III. RESULTS AND DISCUSSION

The proposed separation approach is based on the hypothesis that we can use a single 1D array of cylindrical posts to fractionate a suspension of particles of different size into two streams. The main assumption is that, for a given particle size (and material), there is a critical forcing angle θ_c , that characterizes their motion past the line of posts. Specifically, particles would be displaced laterally by the line of posts for $\theta < \theta_c$ (*deflection mode*), but would pass through the line of posts for $\theta > \theta_c$ (*permeation mode*). The second assumption is that, as observed in previous DLD experiments using 2D arrays of posts, the critical angle depends on particle size, thus leading to size-based separation.[12] In particular, a polydisperse suspension of particles moving past a line of posts oriented at an angle θ , would result in two distinct streams of particles: one permeating through, composed of particles for which $\theta_c < \theta$ and the other deflecting along the line of posts, composed of all the particles for which $\theta_c > \theta$. Moreover, previous experiments in 2D arrays suggest that the critical forcing angle is an increasing function of particle size and therefore, there would be a critical size $a = a_c$, where a is the particle radius, such that $\theta_c(a_c) = \theta$ and smaller

particles ($a < a_c$) would simply permeate through the 1D array of posts but larger particles ($a > a_c$) would be deflected.

A. Probability analysis

In order to investigate the postulated critical behaviour, we analyze the motion and interaction of the particles with individual posts as independent stochastic events in a Bernoulli process. An event here is specific to a particle in a given gap between two consecutive posts. It is defined as a *success* if the particle passes through the gap and a *failure* if the particle does not pass through the gap but gets laterally displaced and continues towards the next gap downstream. Then, we define the probability of crossing, p , as the frequency ratio ν_c/n , where ν_c is the number of successes and n is the total number of events. We also estimate the uncertainty in the determination of the probability of crossing with the variance $\sigma = \sqrt{\frac{p(1-p)}{n}}$. We characterize the downstream output by defining a permeation fraction, $r_p = \nu_c/N$, where N is the total number of particles interacting with the line of posts. The uncertainty in the determination of the permeation fraction is estimated with the variance $\sigma = \sqrt{\frac{p(1-p)}{N}}$. In terms of the experimental variables, θ_c is estimated as the average of lower bound (θ_c^L) and upper bound (θ_c^U) values of the critical transition angle, defined by the highest measured forcing angle corresponding to $p = 0$ and the lowest measured forcing angle corresponding to $p = 1$, respectively.

B. Experimental results

In Figure 2, we present the probability of crossing, p , as a function of the forcing angle, θ , for all particle sizes and the entire range of forcing directions. Each probability value is obtained from an independent experiment at the corresponding forcing angle. In all cases, we observe that the value of the probability is initially zero for a range of forcing directions and sharply transitions to $p = 1$ over a small range of forcing angles. This behaviour is consistent with the directional locking observed in the 2D arrays[12] and with the existence of a critical angle at which the motion of a given size of particles transitions from deflection to permeation, as discussed above. It is also clear in Figure 2 that the critical angle is different for particles of different size, thus indicating the potential for using a single 1D

TABLE I. Critical forcing angles for all particles in single species experiments

Particle diameter	θ_c^L	θ_c^U	θ_c
4.32 μm	$14^\circ \pm 3^\circ$	$20^\circ \pm 2^\circ$	$17^\circ \pm 4^\circ$
10 μm	$14^\circ \pm 2^\circ$	$23^\circ \pm 3^\circ$	$19^\circ \pm 4^\circ$
15 μm	$20^\circ \pm 1^\circ$	$27^\circ \pm 1^\circ$	$23^\circ \pm 2^\circ$
20 μm	$25^\circ \pm 2^\circ$	$32^\circ \pm 2^\circ$	$29^\circ \pm 4^\circ$

array of posts for separation. Both θ_c^L and θ_c^U increase with the size of the particles. The measured values are shown in Table I, where we also estimate θ_c as the average between θ_c^L and θ_c^U . The estimated critical angle also shows the same trend as in 2D arrays.[12]

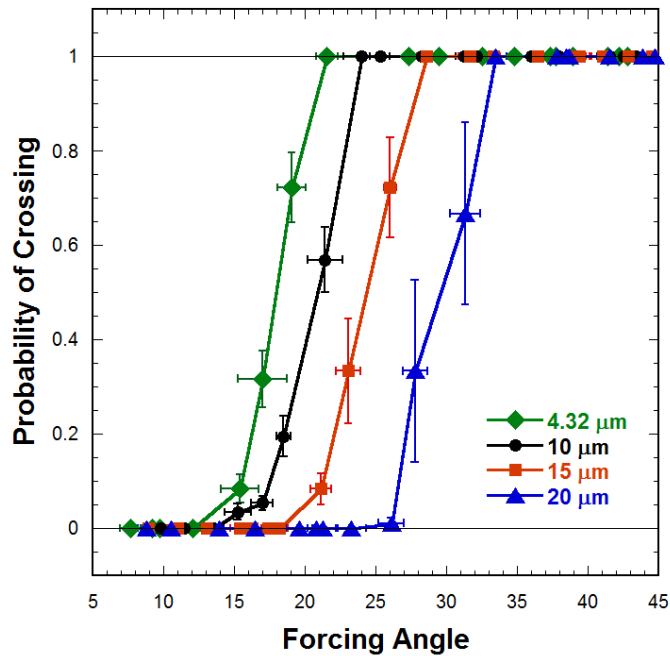


FIG. 2. Probability of crossing, p , for 4.32 μm , 10 μm , 15 μm and 20 μm particles as a function of forcing angle.

The actual separation however, is better characterized by the fraction of particles that permeates through the line of posts, that is the permeation fraction, r_p . In Figure 3, we present r_p as a function of the forcing angle, θ , for all particle sizes. The transition from deflection to permeation is steeper, by definition of r_p , with the permeation angles at which $r_p = 1$ typically reduced by $\approx 2^\circ$ compared to θ_c^U . On the other hand, there is little change in the critical transition angles or the first angles for which the permeation fraction assumes

a finite value, compared to θ_c^L .

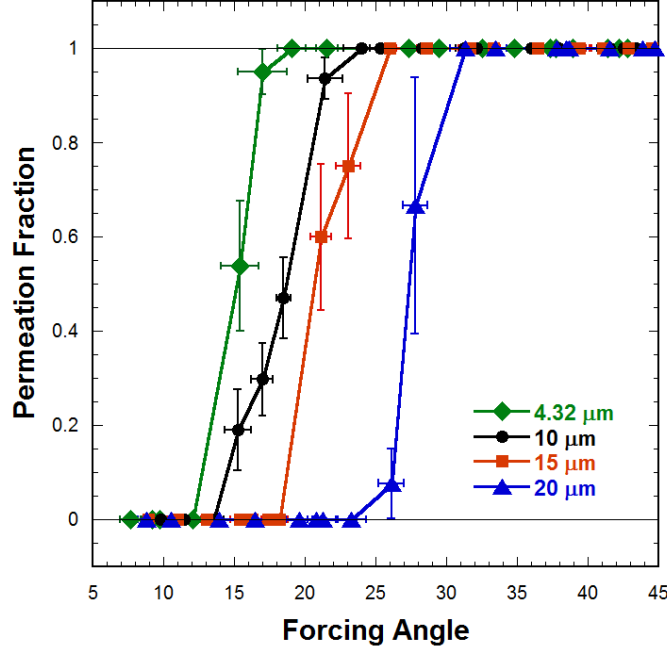


FIG. 3. Permeation fraction, r_p , for $4.32\mu\text{m}$, $10\mu\text{m}$, $15\mu\text{m}$ and $20\mu\text{m}$ particles as a function of forcing angle.

C. Binary experiments and Separability

Based on the results discussed above, obtained for different species separately, we selected specific forcing directions to investigate the separation of binary mixtures of $4.32\mu\text{m}$ and $15\mu\text{m}$ particles and of $10\mu\text{m}$ and $20\mu\text{m}$ particles. The purpose is to identify specific forcing directions where smaller particles permeate through the line of posts while the larger particles deflect. In Figure 4, we present particle trajectories from two representative examples of separation in binary mixtures. In Figure 4(a), the forcing direction is $\theta \approx 15^\circ$ and the $4.32\mu\text{m}$ particles exhibit a finite permeation fraction ($0 < r_p < 1$), whereas the $15\mu\text{m}$ particles are completely deflected along the direction of the line of posts ($r_p = 0$). In Figure 4(b), the forcing direction is $\theta \approx 24^\circ$ and all the $10\mu\text{m}$ particles permeate through the posts ($r_p = 1$), while all the $20\mu\text{m}$ particles are completely deflected ($r_p = 0$). These figures graphically illustrate the probability analysis discussed above, as well as the proposed mechanism for separation.

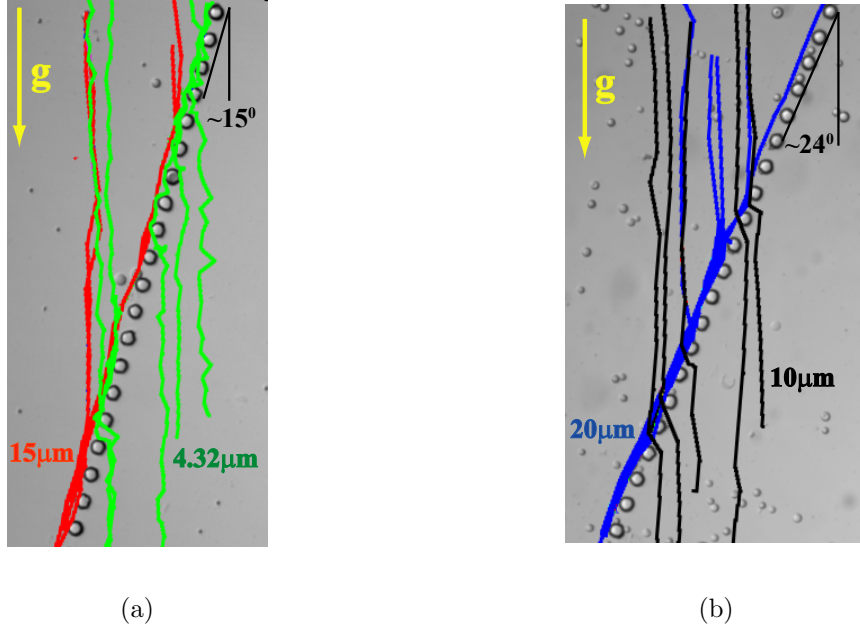


FIG. 4. Representative trajectories during the fractionation of two different binary mixtures. In both cases, we see permeation of the smaller particles in the mixture and deflection of the larger ones. (a) A mixture of $4.32\mu\text{m}$ and $15\mu\text{m}$ particles. $\theta = 15^\circ$. (b) A mixture of $10\mu\text{m}$ and $20\mu\text{m}$ particles. $\theta = 24^\circ$.

In Figure 5, we present the probability of crossing at the selected forcing directions, both in a binary mixture of $4.32\mu\text{m}$ and $15\mu\text{m}$ particles (Figure 5(a)) and of $10\mu\text{m}$ and $20\mu\text{m}$ particles (Figure 5(c)). We also present the permeation fraction, r_p , of the smaller particle and the deflection fraction, $r_d = 1 - r_p$, of the larger particle in both binary mixtures in Figures 5(b) and 5(d). High purity and efficiency of separation can be achieved in both binary mixtures at forcing direction for which, both r_p and r_d are close to 100%. For example, from Figure 5(b), we see that the optimum forcing angle to fractionate $4.32\mu\text{m}$ and $15\mu\text{m}$ particles is around $\theta \approx 18^\circ$. Similar estimation can be made from Figure 5(d) for the separation of $10\mu\text{m}$ and $20\mu\text{m}$ particles, with the optimum forcing direction around $\theta \approx 23^\circ$.

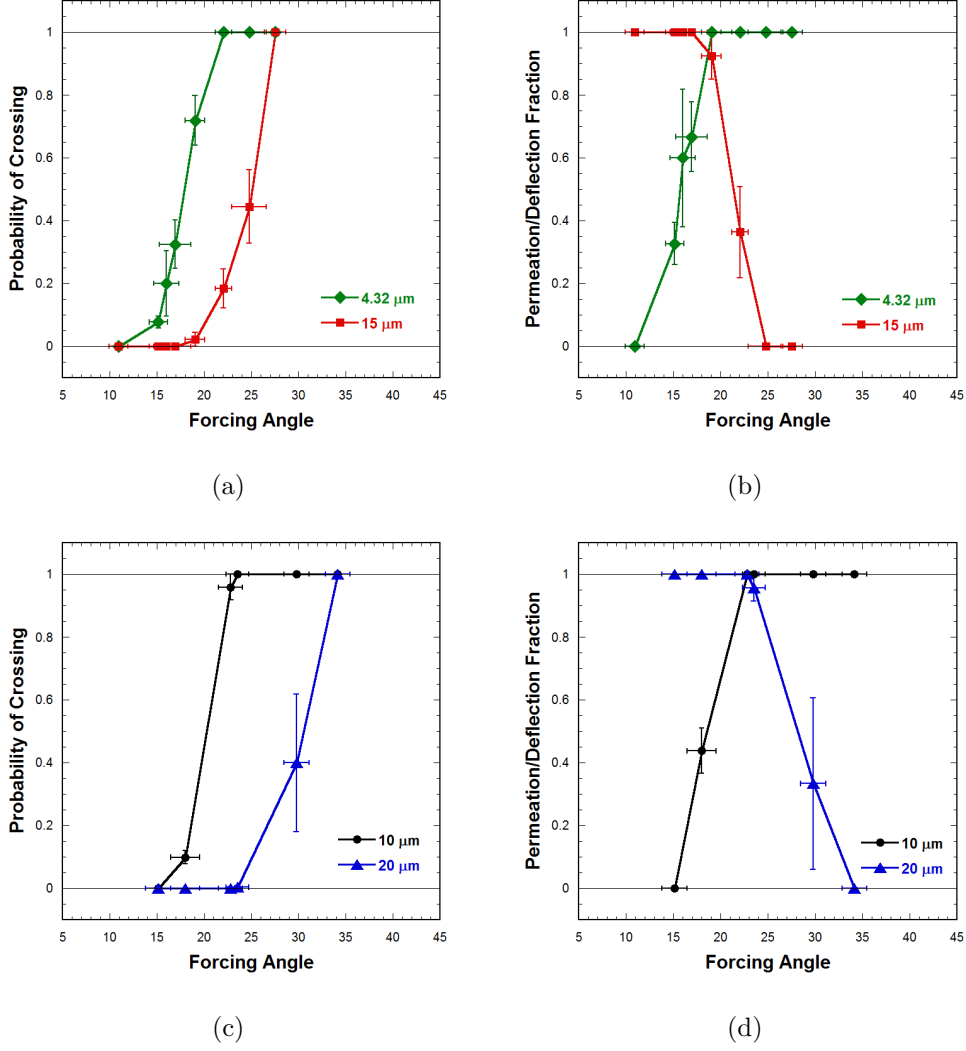


FIG. 5. Probability of crossing for a binary mixture of (a) 4.32 μm and 15 μm and of (c) 10 μm and 20 μm particles. Permeation fraction for 4.32 μm and 10 μm particles and deflection fraction for 15 μm and 20 μm particles in a binary mixture of (b) 4.32 μm and 15 μm and of (d) 10 μm and 20 μm particles.

IV. CONCLUSIONS

We presented a simple and novel method for continuously separating components in a binary mixture using a single 1D array of cylindrical posts. We initially performed characterization experiments, by driving monodisperse suspensions through a line of posts over the entire range of forcing orientations and analyzed the results in terms of the probability of a particle to permeate through the line of posts. In each case, we observed a sharp increase in

the permeation probability over a small range of forcing angles, indicating a transition from deflection to permeation mode as the forcing angle increases from zero. We also showed that the critical transition angle increases with particle size. We finally used these characterization experiments to fractionate binary mixtures at selected force orientations, showing excellent purity and efficiency of separation at angles close to the critical transition angle of the larger particles.

Let us finally note that, the probability of a particle to permeate through the line of posts depends on the number of posts. It is expected that a longer line of posts increases the probability of crossing and thus, the permeation fraction. Hence, increasing the number of posts results in a shift towards lower values of the forcing angle at which all particles permeate *i.e.* smaller θ_c^U . On the other hand, small variations in the size and shape of posts, as well as other effects such as Brownian motion of the suspended particles, could induce early transitions and lower the purity (or efficiency) of the separation. In this sense, a 1D array of posts is more sensitive to defects than a 2D DLD array. Therefore, one should treat the number of posts as a variable used to optimize separation quality or resolution.

The proposed separation approach has similarities with cross-flow fractionation, but it is important to note that in this case the size of the *pores* is larger than the size of the suspended particles and the system is thus less prone to clogging. Finally, let us mention that this method could be enhanced into multi-component separation by positioning consecutive lines of posts at increasing angles with respect to the force (or other arrangements).

ACKNOWLEDGEMENTS

The authors acknowledge technical assistance in particle tracking by Roberto Passarro and Tsung-Chung Feng. This material is based upon work partially supported by the National Science Foundation under grant CBET-0954840.

-
- [1] Alazzam A, Stiharu I, Bhat R, Meguerditchian AN (2011) Interdigitated comb-like electrodes for continuous separation of malignant cells from blood using dielectrophoresis. *Electrophoresis* 32(11):1327–1336

- [2] Balvin M, Sohn E, Iracki T, Drazer G, Frechette J (2009) Directional locking and the role of irreversible interactions in deterministic hydrodynamics separations in microfluidic devices. *Phys Rev Lett* 103(7):078,301
- [3] Belfort G, Davis RH, Zydney AL (1994) The behavior of suspensions and macromolecular solutions in crossflow microfiltration. *J Membr Sci* 96(1):1–58
- [4] Bernate JA, Drazer G (2011) Partition-induced vector chromatography in microfluidic devices. *J Colloid Interface Sci* 356(1):341–351
- [5] Bernate JA, Drazer G (2012) Stochastic and deterministic vector chromatography of suspended particles in one-dimensional periodic potentials. *Phys Rev Lett* 108(21):214,501
- [6] Bowman T, Frechette J, Drazer G (2012) Force driven separation of drops by deterministic lateral displacement. *Lab Chip* 12(16):2903–2908
- [7] Choi S, Song S, Choi C, Park JK (2008) Sheathless focusing of microbeads and blood cells based on hydrophoresis. *Small* 4(5):634–641
- [8] Chung SE, Jung Y, Kwon S (2011) Three-dimensional fluidic self-assembly by axis translation of two-dimensionally fabricated microcomponents in railed microfluidics. *Small* 7(6):796–803
- [9] David W Inglis RHA John A Davis, Sturm JC (2006) Critical particle size for fractionation by deterministic lateral displacement. *Lab Chip* 6:655–658
- [10] Davis JA, Inglis DW, Morton KJ, Lawrence DA, Huang LR, Chou SY, Sturm JC, Austin RH (2006) Deterministic hydrodynamics: taking blood apart. *Proceedings of the National Academy of Sciences* 103(40):14,779–14,784
- [11] De Jong J, Lammertink R, Wessling M (2006) Membranes and microfluidics: a review. *Lab Chip* 6(9):1125–1139
- [12] Devendra R, Drazer G (2012) Gravity driven deterministic lateral displacement for particle separation in microfluidic devices. *Anal Chem* 84(24):10,621–10,627
- [13] Dholakia K, Lee WM, Paterson L, MacDonald MP, McDonald R, Andreev I, Mthunzi P, Brown CTA, Marchington RF, Riches AC (2007) Optical separation of cells on potential energy landscapes: Enhancement with dielectric tagging. *Selected Topics in Quantum Electronics, IEEE Journal of* 13(6):1646–1654
- [14] Dovichi NJ, Zhang J (2000) How capillary electrophoresis sequenced the human genome. *Angewandte Chemie* 39(24):4463–4468

- [15] Frechette J, Drazer G (2009) Directional locking and deterministic separation in periodic arrays. *J Fluid Mech* 627:379–401
- [16] Gossett DR, Weaver WM, Mach AJ, Hur SC, Tse HTK, Lee W, Amini H, Di Carlo D (2010) Label-free cell separation and sorting in microfluidic systems. *Anal Bioanal Chem* 397(8):3249–3267
- [17] Gossett DR, Tse HTK, Dudani JS, Goda K, Woods TA, Graves SW, Di Carlo D (2012) Inertial manipulation and transfer of microparticles across laminar fluid streams. *Small* 8(17):2757–2764
- [18] Green JV, Radisic M, Murthy SK (2009) Deterministic lateral displacement as a means to enrich large cells for tissue engineering. *Anal Chem* 81(21):9178–9182
- [19] Hawkins BG, Kirby BJ (2010) Electrothermal flow effects in insulating (electrodeless) dielectrophoresis systems. *Electrophoresis* 31(22):3622–3633
- [20] Heller M, Bruus H (2008) A theoretical analysis of the resolution due to diffusion and size dispersion of particles in deterministic lateral displacement devices. *Journal of Micromechanics and Microengineering* 18(7):075,030
- [21] Herrmann J, Karweit M, Drazer G (2009) Separation of suspended particles in microfluidic systems by directional locking in periodic fields. *Phys Rev E* 79:061,404
- [22] Holm SH, Beech JP, Barrett MP, Tegenfeldt JO (2011) Separation of parasites from human blood using deterministic lateral displacement. *Lab Chip* 11(7):1326–1332
- [23] Hsu CH, Di Carlo D, Chen C, Irimia D, Toner M (2008) Microvortex for focusing, guiding and sorting of particles. *Lab Chip* 8(12):2128–2134
- [24] Huang LR, Cox EC, Austin RH, Sturm JC (2004) Continuous particle separation through deterministic lateral displacement. *Science* 304:987–990
- [25] Huh D, Bahng J, Ling Y, Wei H, Kripfgans O, Fowlkes J, Grotberg J, Takayama S (2007) Gravity-driven microfluidic particle sorting device with hydrodynamic separation amplification. *Anal Chem* 79(4):1369–1376
- [26] Iwai K, Tan WH, Ishihara H, Takeuchi S (2011) A resettable dynamic microarray device. *Biomedical microdevices* 13(6):1089–1094
- [27] Jaffrin MY (2012) Hydrodynamic techniques to enhance membrane filtration. *Annu Rev Fluid Mech* 44:77–96

- [28] Kantak C, Beyer S, Yobas L, Bansal T, Trau D (2011) A microfluidic pinball for on-chip generation of layer-by-layer polyelectrolyte microcapsules. *Lab Chip* 11(6):1030–1035
- [29] Kirby D, Siegrist J, Kijanka G, Zavattoni L, Sheils O, OLeary J, Burger R, Ducreé J (2012) Centrifugo-magnetophoretic particle separation. *Microfluidics and Nanofluidics* 13(6):899–908
- [30] Koplik J, Drazer G (2010) Nanoscale simulations of directional locking. *Phys Fluids* 22:052,005
- [31] Korda PT, Taylor MB, Grier DG (2002) Kinetically locked-in colloidal transport in an array of optical tweezers. *Phys Rev Lett* 89(12):128,301
- [32] Kralj J, Lis M, Schmidt M, Jensen K (2006) Continuous dielectrophoretic size-based particle sorting. *Anal Chem* 78(14):5019–5025
- [33] Kulrattanakarak T, van der Sman R, Schroën C, Boom R (2008) Classification and evaluation of microfluidic devices for continuous suspension fractionation. *Adv Colloid Interface Sci* 142(1):53–66
- [34] Kuntaegowdanahalli SS, Bhagat AAS, Kumar G, Papautsky I (2009) Inertial microfluidics for continuous particle separation in spiral microchannels. *Lab Chip* 9(20):2973–2980
- [35] Lee SH, Choi SE, Heinz AJ, Park W, Han S, Jung Y, Kwon S (2010) Active guidance of 3d microstructures. *Small* 6(23):2668–2672
- [36] Lenshof A, Laurell T (2010) Continuous separation of cells and particles in microfluidic systems. *Chem Soc Rev* 39(3):1203–1217
- [37] Li Z, Drazer G (2007) Separation of suspended particles by arrays of obstacles in microfluidic devices. *Phys Rev Lett* 98(5):050,602
- [38] Long BR, Heller M, Beech JP, Linke H, Bruus H, Tegenfeldt JO (2008) Multidirectional sorting modes in deterministic lateral displacement devices. *Physical Review E* 78(4):046,304
- [39] Louthack K, Chou KS, Newman J, Puchalla J, Austin RH, Sturm JC (2010) Improved performance of deterministic lateral displacement arrays with triangular posts. *Microfluidics and Nanofluidics* 9(6):1143–1149
- [40] Luo M, Sweeney F, Risbud SR, Drazer G, Frechette J (2011) Irreversibility and pinching in deterministic particle separation. *Appl Phys Lett* 99:064,102
- [41] MacDonald M, Spalding G, Dholakia K (2003) Microfluidic sorting in an optical lattice. *Nature* 426(6965):421–424
- [42] Milne G, Rhodes D, MacDonald M, Dholakia K (2007) Fractionation of polydisperse colloid with acousto-optically generated potential energy landscapes. *Optics Letters* 32(9):1144–1146

- [43] Mittal S, Wong IY, Yanik AA, Deen WM, Toner M (2013) Discontinuous nanoporous membranes reduce non-specific fouling for immunoaffinity cell capture. *Small*
- [44] Pamme N (2007) Continuous flow separations in microfluidic devices. *Lab Chip* 7(12):1644–1659
- [45] Pamme N, Manz A (2004) On-chip free-flow magnetophoresis: continuous flow separation of magnetic particles and agglomerates. *Anal Chem* 76(24):7250–7256
- [46] Pethig R (2010) Review article dielectrophoresis: Status of the theory, technology, and applications. *Biomicrofluidics* 4:022,811
- [47] Risbud SR, Drazer G (2013) Trajectory and distribution of suspended non-brownian particles moving past a fixed spherical or cylindrical obstacle. *J Fluid Mech* 714:213–237
- [48] Sai Y, Yamada M, Yasuda M, Seki M (2006) Continuous separation of particles using a microfluidic device equipped with flow rate control valves. *J Chromatogr A* 1127(1):214–220
- [49] Sochol RD, Li S, Lee LP, Lin L (2012) Continuous flow multi-stage microfluidic reactors via hydrodynamic microparticle railing. *Lab Chip* 12(20):4168–4177
- [50] Stone HA, Stroock AD, Ajdari A (2004) Engineering flows in small devices: Microfluidics toward a lab-on-a-chip. *Annu Rev Fluid Mech* 36:381–411
- [51] Yamada M, Seki M (2005) Hydrodynamic filtration for on-chip particle concentration and classification utilizing microfluidics. *Lab Chip* 5(11):1233–1239
- [52] Yamada M, Seki M (2006) Microfluidic particle sorter employing flow splitting and recombining. *Anal Chem* 78(4):1357–1362
- [53] Yeo LY, Chang HC, Chan PP, Friend JR (2011) Microfluidic devices for bioapplications. *Small* 7(1):12–48
- [54] Zhu T, Cheng R, Lee SA, Rajaraman E, Eiteman MA, Querec TD, Unger ER, Mao L (2012) Continuous-flow ferrohydrodynamic sorting of particles and cells in microfluidic devices. *Micromicrofluidics and Nanofluidics* 13(4):645–654